LCA Methodology

Site-dependent Life-Cycle Impact Assessment in Sweden

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Abstract

Goal, Scope and Background. Although LCA is traditionally a site-independent tool, there is currently a trend towards making LCA more site-dependent if not site-specific. For Europe, site-dependent impact factors have been calculated on a country basis for acidification, terrestrial eutrophication and toxicological impacts. It is, however, an open question whether this is the optimum level for site-dependent factors. The aim of this paper is to develop site-dependent characterisation factors for different parts of Sweden for air emissions of NO_x, SO_x and particulates regarding ecosystem and human health impacts. Based on experiences from a case-study, the usability of the site-dependent factors for LCA are discussed, as well as the appropriate level of site-dependency for ecosystem and human health impacts.

Methodology. The Ecosense model is used for calculating site-dependent factors for some atmospheric pollutants. Characterisation factors are calculated for four different places in Sweden with two different stack heights.

Results and Conclusions. The characterisation factors for ecosystem impacts show fairly small differences between different parts of Sweden (within a factor of two). For health impacts, the differences between different parts of the country were larger and more significant (up to one order of magnitude). Also the difference between low and high stack heights may be relevant, especially in densely populated areas. These results suggest that for ecosystems, site-dependent characterisation factors for the considered atmospheric pollutants on a country level may be sufficient for most applications. However, for health impacts, site-dependent factors on a country level may be inappropriate. Beside LCA, the calculated factors and the methodology used should also be useful for other environmental system analysis tools, such as Strategic Environmental Assessment, Cost-Benefit Analysis and Environmental Management Systems.

Keywords: Air emissions; EcoSense 2.0; ecosystems; human health impacts; NO_x; particulate matter; site-dependent LCIA; SO_x; Sweden

Introduction

LCA is traditionally a site- and time-independent tool where no consideration is given to when and where emissions take place (Udo de Haes 1996). Characterisation factors typically lack site-dependent information, resulting in a site-generic impact assessment (Udo de Haes et al. 2002, Pennington et al. 2004). This is largely due to practical reasons; it is not practically possible to gather site-specific information for all sites included in an LCA. There is, however, a trend towards making LCA more site-dependent if not site-specific (e.g. Bare et al. 2003, Huijbregts 2000, Huijbregts et al. 2003, Krewitt et al. 2001, Nigge 2001a, b, Norris 2003, Potting 2000, Spadaro and Rabl 1999). This can be done by introducing factors that reflect type environments and emission situations. For example, emissions at low height in an urban environment can be differentiated from emissions at a high elevation in rural areas. Impact assessment factors are then calculated for these typical environments. Site-dependent characterisation factors can thus be calculated and used, resulting in a site-dependent characterisation in the LCA.

For Europe, site-dependent impact factors have been calculated on a country basis for acidification by Potting et al. 1998, acidification and terrestrial eutrophication by Huijbregts et al. (2000), and for human health impacts, acidification and terrestrial eutrophication by Krewitt et al. (2001). It is, however, an open question whether this is the most appropriate level for factors of site-dependency. For example, Sweden is a large country (approximately 2,000 km long and 500 km wide) with large differences in population densities. It is therefore of interest to develop site-dependent characterisation factors, also for different parts of a country, to see whether this extra resolution can produce new insights.

There are a number of different environmental system analysis tools which are used in order to study different objects and answer different types of questions (e.g. Wrisberg et al. 2002, Finnveden and Moberg 2005). It is suggested that the type of characterisation factors derived here may be useful also for other tools. One example concerns the Strategic Environmental Assessment (SEA). SEA is a procedural tool with the main purpose to facilitate early and systematic consideration of potential environmental impacts in strategic decision-making such as policies, plans and programmes (PPPs) (Therivel and Partidario 1996, Partidario 1999). The growing significance of SEA as a form of support to decision-making is manifested by the recent EC directive (2001/42/EC) on the assessment of environmental effects from certain plans and programmes (European Parliament 2001). As a procedural tool, SEA can include a number of different analytical tools, for example LCA with or without site-dependent characterisation factors (Finnveden et al. 2003).

Compared to traditional product LCAs, both the possibilities and needs for site-dependent assessments may be larger when LCA is used within the framework of an SEA. This is because there is often some site information available, since the PPP that is assessed often is a PPP for a specific country or region, thus there is some site-dependent information available from the start. There may also be a need to assess whether there are geographical differences related to the consequences of a PPP. For example, there may be a need to assess whether the same PPP can be applied all over a country or a region, or if different PPPs are required.

It is suggested that the site-dependant factors may be useful also in other environmental system analysis tools. For example, in cost-benefit analysis, a distinction is sometimes made between emissions in rural areas and more densely populated areas (Hesselborn and Estreen 2002). In Environmental Management Systems, it may be of interest to differentiate between impacts at different sites of the organisation. In such cases, site-dependent characterisation factors may also be useful.

The aim of this paper is to develop site-dependent characterisation factors for different parts of Sweden for air emissions of NO_x, SO_x and particulates regarding ecosystem and human health impacts. Based on experiences from a case-study, the usability of the site-dependent factors for LCA are discussed as well as the appropriate level of site-dependency for ecosystem and human health impacts.

1 Method

Site-dependent characterisation factors were developed for emissions of SO_2, NO_x and PM by using an integrated impact assessment model, EcoSense 2.0 (IER 2000) in a similar way as is done by Krewitt et al. (2001). Ecosense is an impact pathway model that follows the sequence from emissions of pollutants, through to impacts on receptors (*ibid.*). The characterisation factors were derived by calculating the environmental impact caused by emissions from a well-defined emission source. By using impact models with linear dependence on the amount of emitted substance, the resulting impact could be divided by amount of emission to derive the characterisation factors. Model runs were done in which a hypothetical electricity production plant was located at four different locations in Sweden (**Fig 1**):

- Skåne in the south, close to continental Europe and with a relatively high population density in the surrounding region.
- Västergötland, a bit further north-west, with relatively low population density.
- Stockholm, further north-east, but with a relatively high population density.
- Jämtland in the north, with very low population density.

The dispersion of emissions may vary depending on the height of the emission source. To derive characterisation factors for emission sources at different levels, model runs were made for each site with two stack heights. The characteristics of the model plant are listed in **Table 1**.

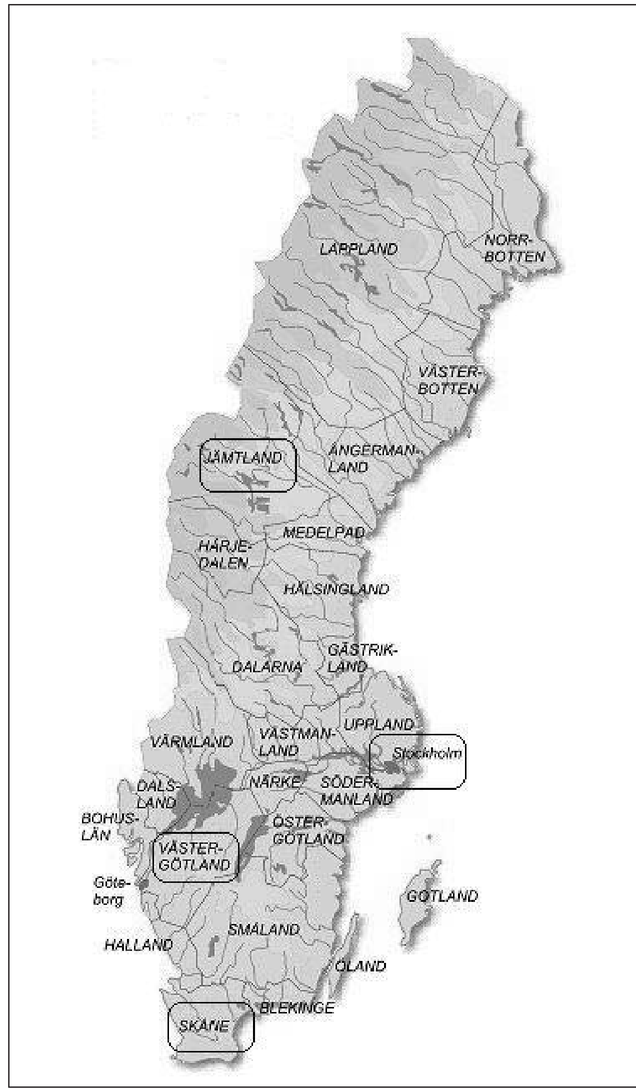

Fig. 1: Location of characterisation sites

Table 1: Characteristics of a hypothetical incineration facility in Ecosense model runs

Parameter	Value
Capacity	138.9 [MW]
Electricity sent out	138.9 [MW]
Full load hours per year	4413 [h]
SO2 Emissions	50.0 [mg/Nm3]
NOx Emissions	50.0 [mg/Nm3]
TSP Emissions	50.0 [mg/Nm3]
Stack height	165.0 [m] / 45 [m]
Stack diameter	3.8 [m]
Flue gas volume stream	570000.0 [Nm3/h]
Flue gas temperature	353.0 [K]
Surface elevation at site	0.0 [m]
Anemometer height	10.0 [m]

The EcoSense model contains two atmospheric emission dispersion models, the local and the regional level. Ecosystem impacts are calculated only at the regional level, whereas human health impacts are calculated at both the regional and the local level. The local and regional human health impacts are added together.

At the local level (corresponding to an area of 100*100 km around the emission source), the Industrial Source Complex Model (ISC) is used to calculate the dispersion of SO_2, NO_x and PM.

At the regional level (covering Europe), the Windrose Trajectory Model (WTM) is used to calculate dispersion of SO_2, NO_x and PM, and the atmospheric transformation into nitrate and sulphate particles as a result of reaction with regional background concentrations of NH_3 (see Krewitt et al. 2001 for further details). The resulting concentrations are linked to exposure response functions on human health impacts and ecosystem impacts. Ecosystem impacts are based on the critical load concept. Human health impacts are based on a risk assessment approach and the functions used are the ones recommended by the ExternE project (Commission for the European Communities 1999). Following the recommendations, we assume a linear relationship between a change in mortality and concentration of pollutants. **Table 2** lists the exposure functions that were selected in Ecosense to derive the site-dependent characterisation factors. The dose response functions used are recommended in the European Commission (1999) after a thorough review of epidemiological literature (Hurley et al. 1997). In particular, our functions on chronic YOLL were derived from Pope et al. (1995), whereas acute YOLL was derived from Anderson et al. (1994) and Toulomi et al. 1994.

Mortality impacts are related to years of life lost ('YOLL') which refers to the expected number of life years lost as a result of the increased pollution. Both chronic and acute effects causing premature deaths do not, on average, occur on 'prime age' individuals, but rather affecting persons with lower remaining life expectancy.

Ecosystem impacts are based on the critical load concept as developed in UNECE convention. The indicator used is the change in actual exposure in an ecosystem area divided by the critical load or level of exposure in this area. The indicator chosen is different compared to Potting et al. (1998) and Krewitt et al. (2001), which used the marginal change in threatened area due to a marginal change in emissions, but similar to the one used by Huijbregts et al. (2001) as their 'above and below critical loads'- indicator. One reason for choosing this indicator is because it allows us to account for the pollution that affects areas that are already above critical loads. The choice of indicators are also discussed by Potting et al. (1998), Krewitt et al. (2001), Huijbregts et al. (2000), Guinée (2002) and Potting et al. (2002).

The following indicators were used:

$$RCW = A * C(X) / C(X)_{crit}$$

$$RDW = A * L / CL$$

Where RCW is the Relative concentration weighted ecosystem area [km^2], A is the ecosystem area, C(X) is the concentration of SO_2 or NO_x, and $C(X)_{crit}$ is the critical concentration of SO_2 or NO_x, RDW is the Relative deposition weighted ecosystem area, L is the nitrogen deposition and CL the critical load of nitrogen. The RCW indicator refers to acidification, whereas the RDW indicator refers to terrestrial eutrophication.

2 Results

The regional analysis shows no great differences in ecosystem impacts (**Table 3**). Västergötland and Jämtland display 20-30% greater impacts, which is probably attributable to being inland emissions rather than coastal emissions. It can also be noted that there is no difference in the results for high and low stacks.

Table 2: Exposure functions selected to derive site-dependent characterisation factors

Receptor	Impact	Pollutant	Reference function
total population	'acute' YOLL	SO_2	Anderson/Touloumi (1996)
adults	'chronic' YOLL	Tsp	Pope (PM)
adults	'chronic' YOLL	Nit	Pope (Nit.)
adults	'chronic' YOLL	Sul	Pope (Sul.)
total ecosystem	RDW N ecosystem area	Nde	UN-ECE 1995 (TOT)
total ecosystem	RCW SO_2 ecosystem area	SO_2	UN-ECE 1993
total	RCW NO_x ecosystem area	No_x	UN-ECE 1993

Table 3: Site-dependent characterisation factors for ecosystem impact of NO_x and SO_x emissions

Emission	Unit	Västerg. (high)	Västerg. (low)	Skåne (high)	Skåne (low)	Stockholm (high)	Stockholm (low)	Jämtland (high)	Jämtland (low)
N (RDW)	km^2/TWh	1.6E+01	1.6E+01	1.4E+01	1.4E+01	1.3E+01	1.3E+01	2.0E+01	2.0E+01
	km^2/kg	7.7E-05	7.7E-05	6.7E-05	6.7E-05	6.4E-05	6.4E-05	9.7E-05	9.7E-05
SO_x (RCW)	km^2/TWh	1.3E+01	1.2E+01	9.7E+00	9.1E+00	8.6E+00	8.1E+00	1.5E+01	1.4E+01
	km^2/kg	6.2E-05	5.8E-05	4.7E-05	4.4E-05	4.2E-05	3.9E-05	7.3E-05	6.8E-05
NO_x (RCW)	km^2/TWh	6.2E+00	6.2E+00	4.3E+00	4.3E+00	3.2E+00	3.2E+00	6.5E+00	6.5E+00
	km^2/kg	3.0E-05	3.0E-05	2.1E-05	2.1E-05	1.6E-05	1.6E-05	3.2E-05	3.2E-05

Table 4: Site-dependent characterisation factors for human health impact of NO_x, SO_x, and particulate emissions

Emission	Unit	Västerg. (high)	Västerg. (low)	Skåne (high)	Skåne (low)	Stockholm (high)	Stockholm (low)	Jämtland (high)	Jämtland (low)
SO_x	YOLL/kg	1.3E-05	1.2E-05	2.0E-05	1.9E-05	8.7E-06	9.1E-06	3.5E-06	3.3E-06
part	YOLL/kg	1.7E-05	1.8E-05	2.9E-05	5.1E-05	1.3E-05	3.8E-05	3.0E-06	3.0E-06
NO_x	YOLL/kg	1.1E-05	1.1E-05	1.7E-05	1.7E-05	6.7E-06	6.7E-06	2.5E-06	2.5E-06

Results for human health impacts are presented in **Table 4**. These are aggregated results for both local and regional impacts. The difference in impacts between different regions in Sweden is approximately one order of magnitude. There is a clear tendency for lower impacts further north, close to a factor 10 between Skåne and Jämtland, and Stockholm and Västergötland in between. This may be due to differences in population densities. The difference between low and high stacks is approximately a factor of 2 for densely populated areas and zero for less densely populated areas.

3 Concluding Remarks

The results for site-dependent characterisation factors for acidification and eutrophication show fairly small differences between different parts of Sweden (within a factor of two). These differences are much smaller compared to the differences between different countries in Europe which can be several orders of magnitude (Huijbregts 2000, Krewitt et al. 2001, Potting 2000). This suggests that site-dependent factors on a country level may be sufficient for the considered atmospheric pollutants except when very detailed studies are made. However, since national borders do not usually reflect different environmental regions, a distinction between different regions would probably be more optimal than a distinction between different countries.

For health impacts, the differences between different parts of the country were larger and more significant (up to a factor of ten). These differences are larger than the difference in country specific factors calculated by Krewitt et al. (2001), suggesting that a country level is not the appropriate level for site-dependent characterisation factors in this case. Whether a factor of ten is considered to be a significant contribution to the overall uncertainty depends on the specific study. The difference between the two stack heights was a factor of two for densely populated areas. However, the lower stack height was still quite high (45 meters). Nigge (2001a) shows that impacts may be higher for emissions on lower levels. More studies to calculate characterisation factors for emissions at ground level from cars, for example, would therefore be relevant.

In this paper we present results for the aggregated impacts from both local and regional levels. Normally, the latter dominates the results. If only local levels are considered, larger differences between lower and higher stack heights are noted (up to a factor of ten for densely populated areas) as well as differences between areas with higher and lower population densities (up to two orders of magnitude) (data not shown).

Although the site-dependent characterisation factors have been discussed in the literature, there are comparatively few case studies published in which site-dependent characterisation factors were used. It is therefore interesting to note that the characterisation factors derived here were applied in a case study showing their applicability (Björklund et al. 2003, Nilsson et al. 2005). This case study concerned a proposed waste incineration tax in Sweden.

In the case study, site-dependent characterisation factors were used to discuss whether there were significant differences in results from different parts of Sweden. If so, this would suggest that different waste policies would be relevant in different parts of the country. It is, however, interesting to note that the results regarding the ranking between alternatives remains the same for the two regions, and that this ranking is the same as in the traditional, not site-adjusted LCA (Björklund et al. 2003, Nilsson et al. 2005). The results thus indicate, although there may be large differences in characterisation factor, that this may not always affect the results and the conclusions from a specific study. However, this result was still policy relevant, since it is often suggested in the public discussions that different policies are needed in different regions. This also indicates that a site-dependent assessment may also be useful when it does not show any significant difference compared to the site-independent assessment.

In this study, the Ecosense model 2.0 was used to derive the characterisation factors. This model uses data on critical loads which is now outdated. This means that the derived characterisation factors should be used with great care and not for detailed assessments.

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